

# COMMENTS ON TECHNIQUES APPLICABLE TO DETERMINATIONS OF SPATIAL DISTRIBUTION OF INTENSITY AND CHROMATICITY<sup>1</sup>

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## ABSTRACT

An instrumentation and method for analysing the spatial behaviour of optical properties of pertinent specimens is described, which performs opto-mechanical scanning with a multi-detector arrangement, uses special amplifiers for modification and a computer for signal evaluation, etc. The instrumentation is capable of identifying colors in the CIE color triangle and of making analyses of spectrographic plates possible by opto-electronic processing, which produces information too laborious to obtain otherwise or which cannot be perceived by direct visual examination of the spectrographic plates, especially if a stigmatic spectrograph has been used for the spectrographic plates.

## INTRODUCTION

Opto-electronic research often requires extensive study of the spatial distribution of optical properties in semiconductor plates, interference filters, etc. The main purpose of this paper is to focus attention on certain modern techniques, which can be used in research or similar efforts and which otherwise would require too laborious an effort. Obviously, in such a publication as this, some of the specialized detailed information may have to be omitted. Readers interested in such detailed information may obtain from the authors a copy of a more extensive manuscript, of which this paper is an excerpt.

The instrumentation described in this paper is a specially designed opto-electronic scanner using three photomultipliers with suitable filtering, nonlinear amplification techniques, and an analog computer, and is called a "Spatial Intensity Distribution and Color Analyzer," which is abbreviated in this paper as SIDCA. It can be used for intensity or spectral analyses, and maps flaws and spatial non-uniformity of optical elements, interference filters, etc., by directly scanning them in transmission or reflection modes. It can show the spatial distribution in emission of light from semiconductors caused by exciting them with other light of different wave lengths. SIDCA can identify colors in the CIE triangle (Gebel 1964, 1967); the analog computer performs operations resulting in the presentation, on an oscilloscope, of the locus in a reference triangle. Artificial color triangles can be made for distinguishing smaller increments in hue or wave length. By scanning spectrographic plates, oscillographic records or new plates can be made which will show detectable information too low in contrast on the original to be perceived, and spatial expansion provides easy evaluation of structures within an apparent line.

### *Arrangements, Techniques Involved and Related Subjects*

The basic schematic of the SIDCA is shown in figure 1. Essentially, the SIDCA comprises the following:

1. The optical section, consisting of a light-tight compartment containing: (a) various light sources, (b) a movable sled on which specimens are mounted, (c) the necessary optical elements for focusing the light from an appropriate source onto the specimen, (d) a semitransparent mirror which permits either transmission or reflection measurements, (e) a beam-splitter arrangement using 30-30 dichroic mirrors so that the detectors can receive light from the illuminated area of the specimen simultaneously, (f) the

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<sup>1</sup>Manuscript received October 13, 1966.



divider, which derives a new signal by dividing that signal obtained by scanning a spectrogram by that obtained from a reference, and (c) an analog computer which may be used to form, from the photomultiplier output, the signals  $-x^\dagger$ ,  $-y^\dagger$ , and  $-z^\dagger$ ; the signals  $X$ ,  $Y$ , and  $Z$ ; the sum  $M$ ; and the ratios  $X' = \frac{X}{M}$ , and  $Y' = \frac{Y}{M}$ , (chromaticity coordinates).

3. The recording section, consisting of: (a) a three-channel recorder, (b) a direct-writing multichannel recorder, (c) an oscilloscope-camera combination, and (d) a glow-discharge tube, modulated by the nonlinear amplifier used to expose a photographic plate on another movable sled.

4. The programmer, which consists of switches that permit selecting the desired operational modes.

The specimens to be scanned are mounted on a motor-driven sled which has a reversible variable speed of 0.25 to 1 mm per second. The sled can be moved in the  $x$  and  $y$  directions and the effective  $y$  position of the aperture may be changed after each line of scan to perform a line-sequential scan with a small aperture. The lens arrangements (fig. 1) used for illuminating the specimen for transmission measurements may be used in a manner which illuminates the specimen with the largest possible amount of light or may serve as a collimator.  $L1$  and  $L3$  are tungsten filament lamps,  $L4$ , a mercury lamp and  $L2$  can be either a tungsten or a mercury lamp, depending on the task.

Using  $L2$  instead of  $L1$  or  $L4$  makes possible easy conversion from transmission studies to reflection studies. In the latter case, one also may have to assure that the light focused on the specimen is within five degrees of the perpendicular to the specimen. In this mode, it is difficult to place an aperture before the specimen in a suitable manner. Placing an aperture too far away would increase the effective area illuminated on the specimen because of diffraction, etc. Therefore, the specimen is illuminated by projecting on it the minified lighted area of a small aperture. This aperture receives its light from a large area light source and acts as a source. Then the effective pupil of the optical system has to be chosen so that none of the rays which form the image on the specimen diverges more than the stated limit of five degrees from the beam axis. The semitransparent mirror, placed between the image lens and the specimen, should be such that the reflectance is about 10 percent, thus permitting use of the largest possible amount of light during transmission measurements of a specimen.

When scanning spectrographic plates, loss of resolution, complications caused by diffraction, etc., which would occur if an area-restricting aperture is placed close to the spectrographic plate, are avoided by placing the necessary aperture before the photomultiplier tube and by focusing an enlarged image of the spectrogram on this aperture. If a slit is used as aperture, its parallel alignment to the spectral lines is critical for best resolution. The linear magnification we use is about 15, which is easily obtained. Thus, a rather large aperture of  $75 \mu$  gives, with a suitable lens, the possibility of observing  $5 \mu$  on the plate. The divergence of the rays, which occurs behind this aperture, does not affect the resolution, because the photocathode integrates all the light.

It is possible to use the same system for spectral scanning by employing three properly aligned apertures before each photomultiplier, or by using a single aperture in the focal plane of the imaging lens and placing the beam-splitter between this aperture and the photomultipliers, which must have large-area photocathodes. The light from the monochromator (fig. 1) can be injected into the system at several different places. The solution shown in the basic schematic diagram has been chosen so that the light from the monochromator will pass through all the important elements which are usually involved in the measurements. Then, using an intensity-calibrated monochromator and the three-channel recorder, one can conveniently check the overall intensity response as a function of wave length for the entire system.

For determining colors with SIDCA, as with the human eye, the X, Y, and Z responses of the eye can be sufficiently well represented by the following filter-photosensor combinations:

X-( $X_{450}$  and  $X_{600}$ ).  $X_{450}$  is used to refer to the portion of the X curve with a peak at about 450 m $\mu$  and  $X_{600}$  is used to refer to the portion of the curve with its peak at about 600 m $\mu$ . Because, at present, there seems to be no single filter available which gives both peaks and, hence, can be used with a single photomultiplier, the combined output of #48 Kodak filter with a 1P28 photomultiplier (S-5) and #23A Kodak filter with a 1P2 photomultiplier (S-4) is a solution.

Y-#106 Kodak filter and #600 Optics Technology shortwave pass filter with a 1P21 photomultiplier.

Z-#48 Kodak filter with 1P28 photomultiplier. (The filters mentioned were those used for our instrumentation, but obviously any other filters with equal characteristics may be used.)

Because only 3 photomultipliers had been incorporated in SIDCA, the omission of the 1P28 photomultiplier with the #48 filter for  $X_{450}$  was made possible by substituting a portion (0.17) of the Z signal and mixing this with the X signal obtained with the 23A filter. The proper proportions between the signals were maintained through the use of neutral density filters, amplifier-gain adjustments in the computer, and gain adjustments of the photomultipliers, by adjusting the voltage of their power supplies within the range over which the relative spectral response was sufficiently constant.

The common failure of 30-30 dichroic mirrors (fig. 1) to transmit and reflect with flat spectral responses must be considered in choosing the appropriate filter-photosensor combinations. Neutral density filters must be used with the filter-photodetector combinations to balance the values of X, Y, and Z with respect to each other, although additional adjustment can be made in the computer.

The recorders used must have adequate frequency response to record the transient changes expected. The following reasoning is usually used to determine adequate frequency response. For optimum resolution, the sled should be run at its slowest speed, which in our instrument is 250 microns per second. The smallest effective slit width in our instrument is 5  $\mu$ . Hence, a transient is achieved in  $\frac{1}{250/5} = 20$  milliseconds. In practice, it has been found that the numerical value of the upper frequency cutoff of the amplifier should be four to five times the reciprocal of the input transient time for sufficiently maintaining the original wave form. This, in our case, is 200 to 250 cycles per second; the visicorder used has a frequency response of 0 to 200 cycles per second, which fulfills this condition. The visicorder utilizes a mirror galvanometer deflecting an ultraviolet beam of light, which is then recorded on ultraviolet-sensitive photographic paper (trace visible a few seconds after exposure without further development; however, to obtain very good traces, chemical development may be used). A polaroid camera may be attached to the oscilloscope and will provide, in a convenient way, photographic records when the slow-speed sweep generator is used. In many cases, such recording may be sufficient; however, the records obtained with the visicorder are more accurate. When the oscilloscope is used for recording, a dual-beam scope may be used, where the trace of the second beam is used to indicate the position of the movable sled by pulsing the second beam on and off. Storage reproducers may be used in addition to the other recording devices shown in figure 1. Thus, the signals from the scanning of a specimen may be stored and then reproduced simultaneously when scanning is completed. For some applications, this type of recording may be more desirable than the time sequential record.

If single interference filters are used to produce nearly monochromatic light, their leakage plus the spectral characteristic of the specimen (crystal) plus the wave length dependency of the light source may shift the effective spectral region

of the light reaching the photomultiplier considerably away from the peak of the interference filter. The term "leakage" is usually used for the non-negligible fraction of the overall transmission, which is represented by the tail of the curve of the filter characteristics. This tail may continue over a wide wave length interval. In such a set-up, the dominant element which determines the spectral distribution of the light reaching the photomultiplier may be the specimen and

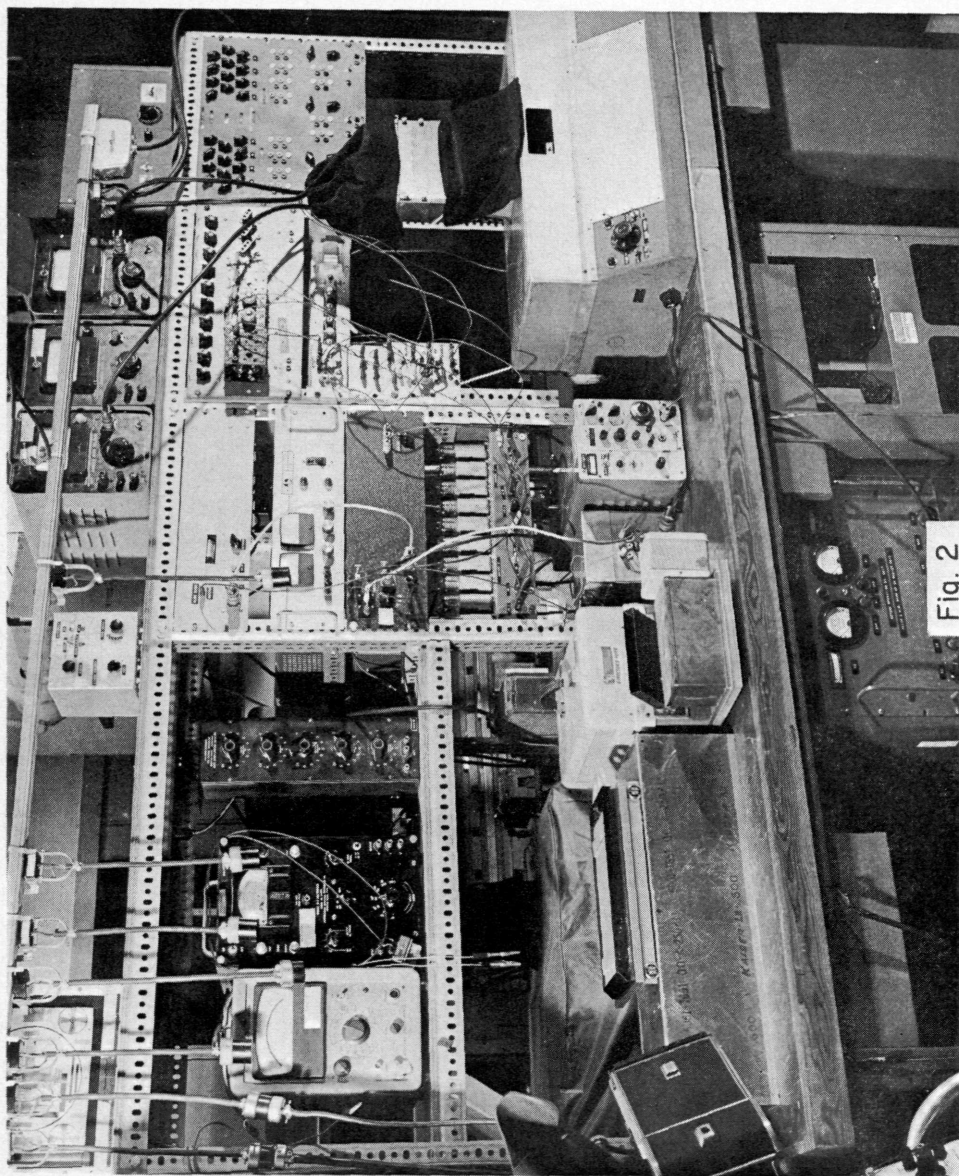


FIGURE 2. The Spatial Intensity Distribution and Color Analyzer. (SIDCA)

not the interference filter. Hence, in order to use light effectively only within the band pass of the interference filter, and to avoid erroneous results from the leakage, multiple interference filters or a monochromator may have to be used. The optical system was designed for maximum adjustment in all planes, with enough precision to assure good resolution, and uses visual observation for focusing, necessary especially for spectral-line structure study.

Position indicators of various design may be used for the movable sleds for determining the  $x$  and  $y$  positions. For example, an electrical contact can be intermittently activated by the specimen sled, and the sequence of the pulses coded to indicate the position of the specimen and the  $y$  position of the aperture. Alternatively, a photocell can be used to produce the identification pulses by receiving light coming through a sequence of holes in the sled, which are also affected by the  $y$  position of the aperture. At the reproducer, a glow discharge tube may be used to reproduce the code sequence.

Since a transmission or reflection spectrogram represents the overall spectral composite of lamp and specimen, and the emission from the lamps usually used has a high spectral dependency which causes a gradient in the plate background density, easy and precise recognition of faint information superimposed on this background is often a problem. With the help of SIDCA, one may produce spectrograms within certain spectral regions which show the information of the specimen, but only a very small amount of the background caused by the lamp. One method for achieving this result requires taking a spectrogram of the lamp by itself on the same photographic plate as the composite spectrogram. Both spectrograms are then scanned simultaneously, using two photomultipliers. The signals obtained this way are divided, one by the other, the results of which then, using the nonlinear amplifier as a variable threshold limiter, yields a signal which may be free of the lamp background. Obviously, the effective light flux used for the reference and the composite spectrograms should be as nearly identical as possible in order to minimize the influences of any nonlinearities in the photographic process. If the new recording does not have to express the ratio of the flux incident on the specimen to the flux received by the spectrograph for the composite, but is merely needed for correctly determining the wave length of the spectral lines of interest, then a simple subtraction of the two signals may be made by feeding the two photomultiplier outputs into a ground symmetrical amplifier, which acts as a differential amplifier, before using the nonlinear amplifier.

A line-sequential scan, which requires a small suitable aperture, should be used for scanning optical elements, etc., for spatial effects, to assure the highest detectivity of flaws and inhomogeneities, even if this operation may require considerable time for large-area specimens. To find specimens free of defects, one may be inclined to determine their flawlessness by a single scanning of the specimen, using a rectangular slit which has the length equal to the side length of the specimen, although any uniform striations extending across the specimen in the direction of the line of scan (parallel or nonparallel) would not be detected. In order to find perfect specimens, it may be possible to eliminate some which are not obviously defective to the eye by first scanning with a rectangular slit. Then line-sequential scanning with a small aperture is only necessary for the ones which did not appear defective in the rectangular-slit scanning. Such a combined method may save time. If the chosen dimensions of the aperture are not sufficiently small, very small surface defects (minor scratches, etc.) may not show up in the signal when scanning.

When using SIDCA for color analysis, one must remember that different compositions of light can cause the same ratios,  $-X/-M$  and  $Y'$ , depending on the spectral characteristics selected for the detectors, and, therefore, more than one artificial color triangle may, in some cases, have to be used for the same specimen, in order to reveal inhomogeneities. Further, one must consider that intensity

changes of the light being analyzed will not cause a change in the  $X'$ ,  $-X/-M$ , or  $Y'$  signals, if the instrument is operated in an appropriate mode. However, if several identical-pass filters are superimposed, the effective steepness of the edge of the combined wave length characteristic of the filters increases, which changes the effective weight of the polychromatic light on the detectors and, hence, the ratios formed by the computer, so that a spectral change is recorded. It is necessary to consider this because specimens of uniform composition but of varying thickness will cause the same effect.

When performing opto-electronic processing of spectrographic plates, one should not overlook the following limitations of the photographic process and the spectrographic arrangement. When a photographic plate is exposed to a fine pattern of light, the congruency of the reproduced pattern to the original is not determined by the size of the developed grains alone, but also by other factors. Furthermore, the location of a point image may not be exactly identical with the location on which the light was focused. (Kodak quotes that these apparent image movements rarely exceed 10 microns.) Whenever the intensity of an image focused on a photographic plate has sudden spatial changes, the recording shows a spatial transient for each spatial change in illumination, which is related to the type of configuration of the pattern and affected by the developing conditions. Because this may falsify the accuracy of the results, it must be considered when recording fine spectrographic lines and cannot be neglected in the evaluation of certain spectrographic plates. The different effects, which can cause such a spatial dependency as a function of configuration and developing method, have been collectively called the adjacency effects. (Kodak Photographic Plates for Scientific and Technical Use, by Eastman Kodak Comp., Rochester, N.Y.) These effects are mainly due to chemical reaction products which are produced during the developing process and which diffuse from a region of heavier exposure into one of lesser exposure and, likewise, of the diffusion of fresh developer from a less exposed area into regions of higher exposure. Furthermore, the reaction products accumulate in certain regions to a greater extent than in others. This all results in a gradient pattern of effectiveness of the developing action over the entire plate, which yields unequal results for equal exposure of light. That is, it introduces a spatial nonlinearity in the faithfulness of the recording.

Nonlinearities in density resulting from the failure of reciprocity may be calculated into the results in determining the original light flux from a photographic plate, but to compensate for errors introduced by the adjacency effects is nearly impossible, because of the different and complex situations which may exist and may cause different kinds of distortions. Heavy agitation of the developer will considerably reduce the adjacency effects, but not completely eliminate them. In evaluating structures of spectral lines or closely spaced spectral lines, a test of the entire process and instrumentation should be performed by exposing the plate with a line of known structure and with close lines of known spacing and intensities.

Spectrographic plates made with the better grating spectrographs (grating with  $N \approx 220,000$  lines) usually have a plate factor (this factor times linear distances between centers of lines on spectrograms gives wave length differences between lines) of  $2\text{\AA}$  per mm. Monochromatic light, no matter how narrow its true bandwidth, is treated by the spectrograph, because of its limiting angular resolution, as light having a minimum bandwidth of

$$\Delta\lambda = \lambda / (mN),$$

where  $m$  = spectral order. Therefore, when light with  $\lambda = 4400\text{\AA}$  and  $m = 1$  is used, the smallest possible linear width ( $W_{\min}$ ) of a line on a spectrographic plate taken with an instrument with the above specification is 10 microns, regardless of how narrow the true bandwidth is, and thus it is the same as if caused by monochromatic light with a bandwidth of  $0.02\text{\AA}$ . Hence, in such an instrument, one source at  $\lambda$

and the other at  $\lambda + \Delta\lambda$  will appear as one single line with a width of  $2 W_{\min}$  (20 microns for the above example). Obviously, when several spectral lines fuse, the structure of the resulting line depends on their true separations, true bandwidths, and the intensity ratios of the sources. To prevent fusing, as in the above example, it would be necessary to use a higher  $m$  or to increase  $N$ .

Scanning fused lines on a spectrographic plate with SIDCA, by setting the threshold limiter to an appropriate level, may show single lines on the new recording, if the line caused by the fusing had a suitable structure for this process, even if the true separation of the sources was less than  $\Delta\lambda$ . The smallest obtainable width of line in the above example matches the maximum value of the apparent image movement on the spectrographic plate, which means that the uncertainty of the location of the line is that quoted by Kodak. To reduce the effectiveness of this apparent image movement and the previously explained adjacency effects, one would have to increase the plate factor, but, because an increase in the plate factor spreads the available number of quanta over a larger area, failure of photographic reciprocity may become a problem when recording weak lines. This may make the use of light amplification or of the Lallemand Electronic camera (Lallemand, Duchesne, and Wlerick, 1960) necessary, where the latter gives a gain in sensitivity of 100 or more and no failure of photographic reciprocity occurs.

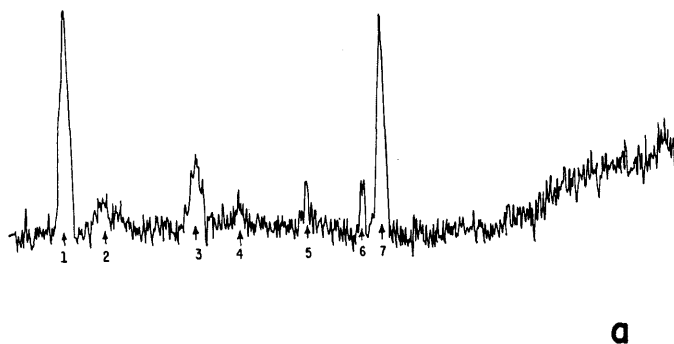
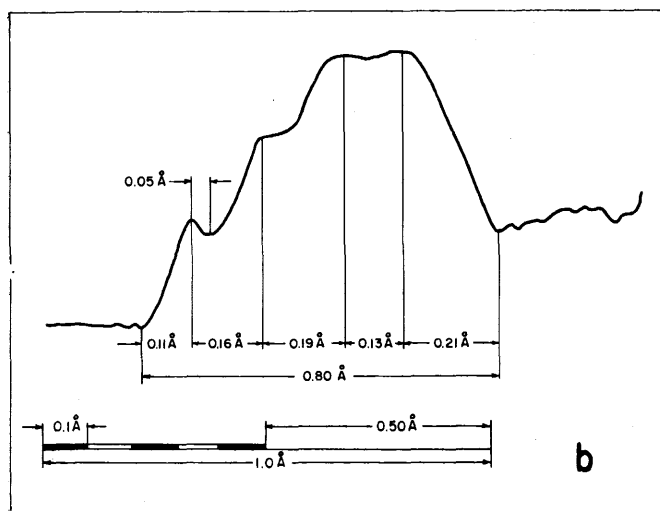


FIGURE 3. Recordings Obtained by Scanning Spectrographic Plates with SIDCA.

a. Result of scanning plate on which lines 2 through 6 were not perceptible by direct visual observation.



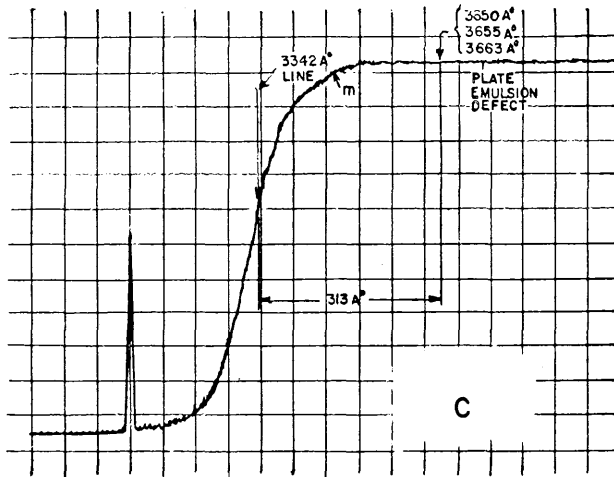
b. Expanded structure of a spectral line.



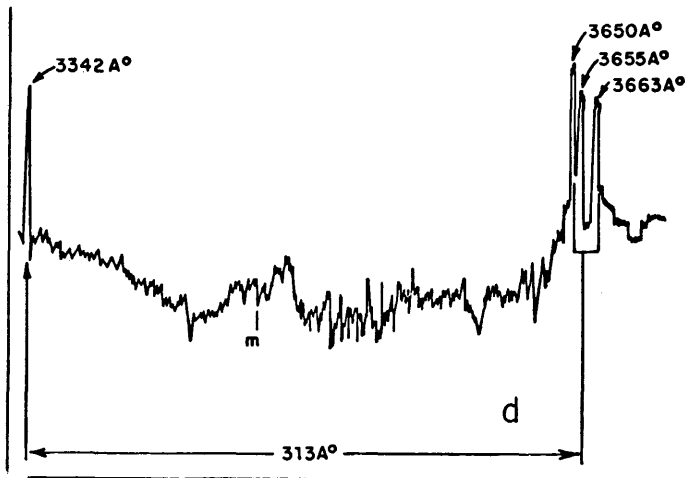
*Typical Examples of Results Obtained with SIDCA*

Visicorder traces obtained by scanning spectrographic plates with SIDCA are shown in Figure 3. Several spectral lines, too faint to be visually distinguished with certainty from the background of the original plate, can be recognized in figure 3a. Figure 3b shows the structure of a spectral line, which appears to the unaided human eye as a single line on the original. Figure 3c shows a trace obtained by scanning a plate in a conventional manner, with a reflection spectrum

FIGURE 3 (Continued)



- c. Recording obtained by conventional scanning of spectroscopic plate with large intensity gradient.



- d. Result of scanning the indicated area of plate of c with SIDCA, using variable threshold suppression.

obtained by using a tungsten lamp. Figure 3d shows the trace obtained by scanning the plate used for 3c and using a changeable threshold in the threshold-amplitude limiter to compensate for the spectral fade-out of the illuminating source. Figure 3e depicts the deviations in the spectral characteristic of different resolution elements on the same crystal by showing a series of spectrograms made by scanning the same stigmatic spectrographic plate several times with an appropriate vertical displacement and using an effective aperture of  $10\ \mu$  width by  $100\ \mu$  length for SIDCA. The true limiting vertical spatial resolution of the spectro-

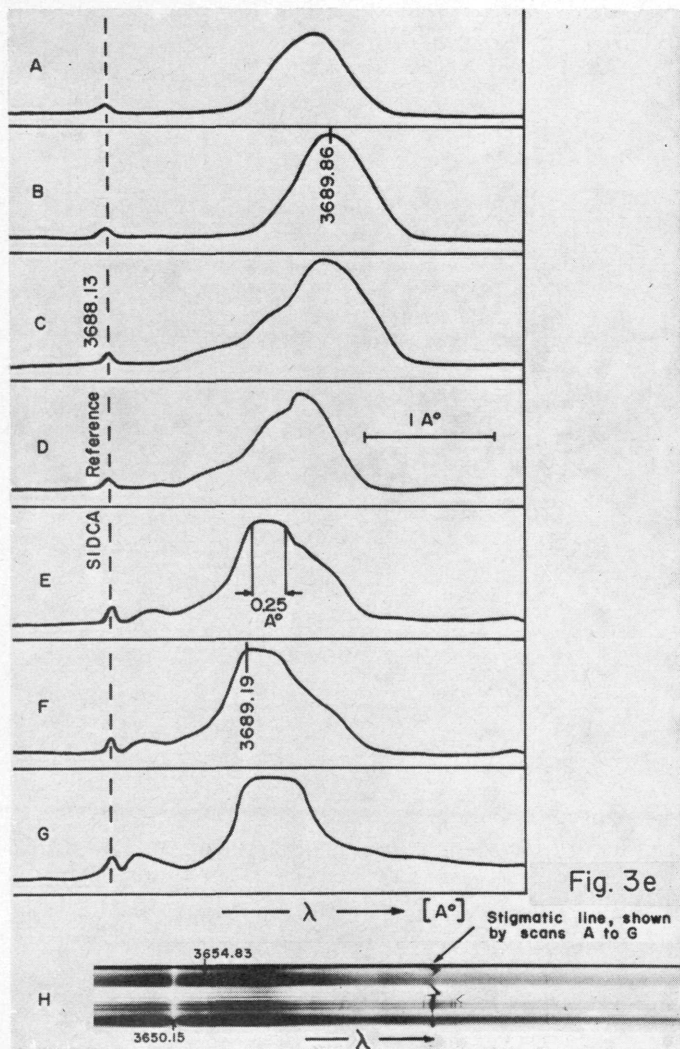
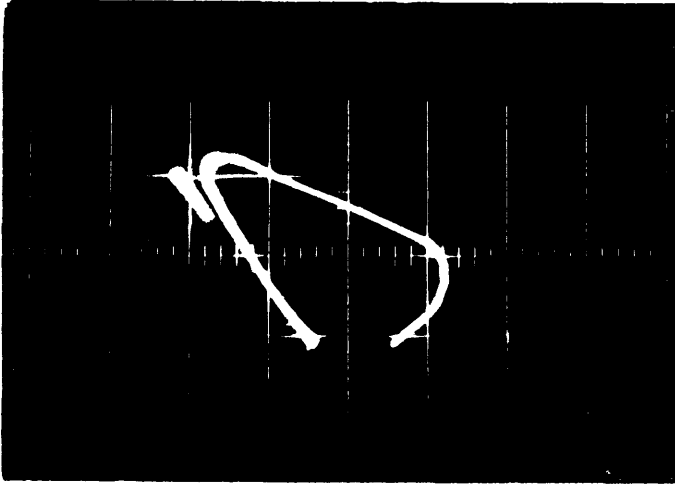


FIGURE 3 (Concluded)

- e. Separate spectrograms of individual resolution elements (A to G), obtained by SIDCA scanning of spectrographic plate (H), made with B&L stigmatic grating spectrograph (220000 line grating) which show the emission from a ZnO (Se) 0.1% Na specimen, excited by a Hg lamp. Only traces with most significant spectral deviations are shown. Resolution element size on crystal: Vert.  $20\ \mu$  (SIDCA aperture), hor.  $50\ \mu$  (Spectrograph slit width).

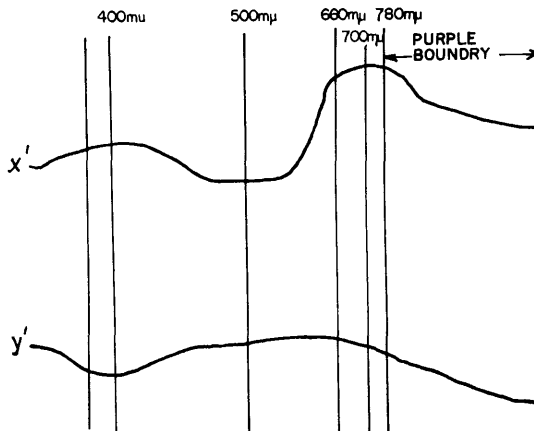
graph was determined to be  $20\ \mu$  by imaging a fine-mesh screen on the slit of the stigmatic spectrograph. In performing these measurements, one must not overlook the limitations set by the adjacency effects, discussed earlier.

In another use of SIDCA, a verlauf filter ( $4000\text{\AA}$  to  $7000\text{\AA} \approx 3\text{ cm}$ ) was used to produce visicorder traces of  $X'$  and  $Y'$  and to obtain an on-scope color triangle (figure 4) closely resembling the CIE color triangle standard. An interference



**Fig. 4a**

FIGURE 4 a. Oscilloscope trace recording showing the color triangle obtained by scanning a verlauf filter. The trace outside the triangle was obtained by scanning a heat-damaged narrow-band-pass, interference filter.



**Fig. 4b**

b. Visicorder trace of verlauf filter of 4a.

filter that changes its wavelength spatially in a continuous manner is variously called an interference wedge, a gradient filter, a verlauf filter, or, for short, verlauf. However, the triangle plotted on the scope fell inside the CIE color triangle, due to several factors: leakage of the verlauf filter, the fact that the slit used (0.25 mm effective resolution) would pass a fairly wide spectral band ( $\approx 25\text{\AA}$ ) from a verlauf of the size used, failure of the detector responses to exactly duplicate the human eye responses, and failure of the source to duplicate CIE standard "white light". Correcting all the above errors would give the true color triangle.

With the same arrangement, commercial interference filters were tested for their uniformity. Surprisingly, deviations in wave lengths of as much as  $\pm 12\text{\AA}$



Visicorder trace obtained by scanning a scratched, clear-glass plate.

Fig. 5

were found in some of the better quality filters. The instrument was sensitive enough so that the small amount of leakage in a filter with a half-intensity bandwidth of  $100\text{\AA}$  caused the oscilloscope record to fall inside the CIE color triangle, rather than on its perimeter, but closer to the true perimeter of the CIE color triangle than with the verlauf filter. Figure 4 shows the trace of a heat-damaged interference filter. Figure 5 illustrates the visicorder trace of the spectral effect caused by a scratch on a high-quality optical glass obtained by using (before the photomultipliers) close-spaced interference filters which had their peaks at 4660, 5000, and  $5330\text{\AA}$ .

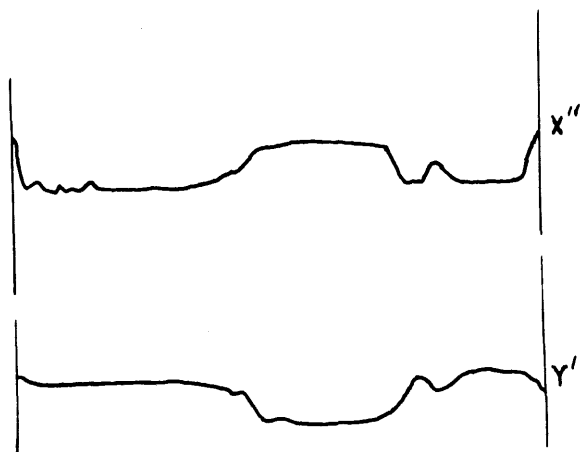


Fig. 6b

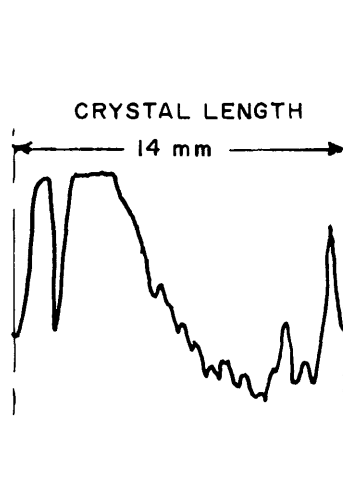


Fig. 6a

FIGURE 6. SIDCA recording obtained by scanning a CdS platelet having striations.

- a. Recording of intensity of transmitted light of  $5000\text{\AA}$ .
- b. Recording of changes in spectral composition of transmitted light caused by striations using close-spaced interference filters for the three detectors.

The change in the intensity of the light transmitted through a cadmium sulfide platelet with striations, found with a single 1P21 photomultiplier and a 5000Å filter, is shown in Figure 6a. Figure 6b shows the visicorder recording of the X" and Y' signal of the same platelet. The previously described close-spaced interference filters (4660, 5000, and 5330Å) were used, and the trace shows spectral effects caused by thickness changes not perceivable by the unaided eye nor in a scanning mode based on the human-eye tristimulus responses.

The authors are hopeful that this paper may provide information useful to those working in endeavors requiring such techniques.

#### ACKNOWLEDGEMENT

This research was supported by the "ARL In-House Independent Laboratory Research Fund". The support of Colonel Robert E. Fontana, Commander of the Aerospace Research Laboratories, is gratefully acknowledged. We also wish to express our gratitude to Mr. Donald C. Reynolds, Director of the Solid State Physics Research Laboratory, for technical review and helpful criticism. Our sincere thanks are expressed to Mr. Henry Bost for making the mechanical arrangements and to Mr. Roy Hayslett and Mr. William Woody for general assistance and technical support. Appreciation is also expressed to other colleagues for stimulating discussions, and for the helpful suggestions of the reviewers of The Ohio Journal of Science.

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